Technical Progress Report

Studies of the Longitudinal Instability with an Electron Beam

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University of Maryland
College park, MD 20742

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UNIVERSITY OF MARYLAND

**LABORATORY FOR PLASMA RESEARCH
COLLEGE PARK, MARYLAND
20742-3511**

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1. Introduction and Summary

This progress report covers the research on the "Longitudinal Instability with an Electron Beam" performed at the University of Maryland during the first year (beginning August 1, 1992) of the two-year grant sponsored by the Department of Energy, under Grant No. DEFG02-92ER54178. We stated our goals for this first-year period in the Proposal as follows: "Our primary goal for the revised first year program will be to study the evolution of a small perturbation in the current pulse (introduced via the grid voltage on the electron gun) when the beam propagates through our 5-m long periodic solenoid channel. Specifically, we want to see if the perturbation is reflected from the rear end of the pulse. If time permits, we also want to get started with the resistive-wall experiment in the 1-m long solenoid as described in Section 4a of the proposal. However, we do not expect as much progress as we had originally anticipated."

So far these objectives have been met without any delays, and, indeed, the results have been far more interesting than we originally expected. We were able to launch different perturbations on the beam resulting in either a slow space-charge wave or a fast wave or both waves. The relative strength of each wave was found to depend on the electron emission temperature of the cathode. The propagation of these waves on an initially rectangular longitudinal beam profile was measured with fast current monitors and the kinetic energy was measured with sensitive energy analyzers at various positions along the 5-m long solenoidal focusing channel. We have also begun to study the behavior of the waves when they reach the respective edge of the beam. But this work is still of a preliminary nature, and we need to refine the beam conditions and measurements in future studies to reach any firm conclusions. Preparations for the resistive-wall instability experiment are in progress. We received a resistive glass tube from China, but it may not be acceptable due to nonuniformities in the resistive layer near one end of the tube. Negotiations with the Chinese Institute manufacturing these tubes are in progress.

A brief, but more detailed, report on our work so far is given below. The Appendix contains copies of several papers that are relevant to our work. We expect to present papers on the ongoing research covered by this grant at the 1993 Particle Accelerator Conference in Washington (May 17-20, 1993) and at the International Symposium on Heavy Ion Inertial Fusion in Frascati, Italy (May 25-28, 1993).

2. Study of propagation of local perturbations on electron beams

2.1. Experimental setup

The experiment to study the propagation of local perturbations on electron beams has been performed on our Electron Beam Transport Facility consisting of the 5-m long periodic solenoid channel and the short pulse electron beam injector. A schematic diagram of the experimental configuration is shown in Fig. 1 which is described in some detail in reference 1.

Fig. 1. Schematic diagram of the experimental configuration.

The short pulse electron beam injector [2] consists of a variable-perveance gridded electron gun, an induction acceleration module and three matching lenses. The electron gun can produce the beam in wide parameter ranges: beam energy up to 10 keV, beam current up to hundreds of milliamperes, minimum beam pulse duration down to a few nanosecond, etc. The initial perturbation on the beam is also generated by the gun. The induction module can impart an energy tilt to the beam bunch. The matching lenses match the beam from the injector to the long solenoid channel. This injector was developed in the last few years to study the longitudinal beam dynamics.

The long periodic channel has been employed for study of transverse beam dynamics for many years [3]. It was modified last year to study longitudinal compression of space-charge dominated electron beams. Thus, we have installed five fast current monitors, two retarding field energy analyzers, and one deflecting energy analyzers at several locations along the channel, as indicated in Fig. 1. The vacuum of the channel system has also been

improved by more than one order of magnitude to satisfy the requirement of the gun operation.

2.2. Generation of initial local perturbations to the beam

The local perturbations are introduced to the beam through the grid-cathode pulse on the electron gun [4]. As shown in Fig. 2, the grid-cathode pulse of the electron gun is produced by an electronic circuit consisting of a chargeable transmission line, a fast avalanche switch, and a DC bias supply. The pulse is usually formed in a rectangular shape which controls the beam current. By introducing some discontinuity to the transmission line, a small bump of excessive voltage will appear on the grid-cathode pulse as a local perturbation which is shown in Fig. 3. This corresponds to an initial velocity perturbation to the beam which in general will produce the beam density and/or current perturbations. By changing the location of the discontinuity, one can move the perturbation from the beam front to the beam end.

Block diagram of the gun electronics

Fig. 2. Circuit diagram showing the way to generate local perturbations.

Fig. 3. Grid-cathode pulse with local perturbations.

2.3. Propagation of local perturbations on the beam

As was expected, a local velocity perturbation on the beam at the gun initiates two space-charge waves: a slow wave and a fast wave. When the beam moves downstream, the two space-charge waves with the same amplitude propagate in opposite direction in the beam frame and separate from each other with the so called "sound velocity". This theoretically well-known phenomena was verified in our experiment as a starting point.

In the experiment the beam and the perturbations are diagnosed by the five fast current monitors and three energy analyzers. Fig. 4 shows the current waveforms with the perturbation, measured by the current monitors. On the left of the figure the current waveform is from the first current monitor which is 0.624 m away from the electron gun. On the right, the current waveform is measured by the fourth current monitor at a distance of 4.3 m from the gun, illustrating the increasing separation with distance of the two space-charge waves. The energy measurement by the second retarding field energy analyzer is shown in Fig. 5 where the excess energy of the two waves above the beam average energy is plotted. Fig. 6 shows the separation of the two waves as a function of the propagation distance. A comparison with theory is also made in the figure.

Fig. 4. Current waveforms with perturbation from the first current monitor (left) and the fourth current monitor (right), showing propagation of two space-charge waves where F denotes the fast wave and S is for the slow wave.

Fig. 5. Excess energy carried by two space charge waves, measured by the second retarding field energy analyzer.

Fig. 6. Time interval between two space-charge waves vs. drifting distance. The stars are the data points from the wall-current monitors, the crosses represent the measured data from the energy analyzers, and the solid line is from theory. The rather larger deviation of the last two points from theory is not yet understood.

2.4. Various forms of space-charge waves

To our surprise and confusion in the early experiment, sometimes only one fast wave was observed which propagated towards the beam front edge; sometimes only one slow wave was observed which propagated towards the beam tail edge. The waves on the beam current waveform had also different polarities and the energy carried by the waves had different values. This seemed contradictory to what we understood about the space-charge waves.

The clue to this puzzle was found when we noticed in the experiment that the initial density and current perturbation due to the velocity perturbation in our gun configuration depended strongly on the emission condition of the cathode. Under the space-charge limited case where the cathode was in a good emission condition and the beam current was space-charge limited, the grid-cathode voltage change produced very little beam current change. However, under the temperature limited case where the cathode emitted not so well and Child's law was not satisfied, the perturbation bump on the grid-cathode pulse

would cause a relatively large beam current change. Under some conditions it seemed that the grid-cathode pulse perturbation even produced a negative beam current perturbation, which is not fully understood yet. This resulted in the various forms of space-charge waves in the experiment.

The properties of the space-charge waves in the experiment were determined by the initial conditions of the perturbation which were closely related to the cathode emission conditions. With the same perturbed pulse between the grid and cathode, the initial beam current perturbation could be significantly different if the cathode emission changed. As an example, Fig. 7 shows three beam current waveforms from the first wall-current monitor where all the conditions in the measurement were the same except that the cathode emission was changing by heating up the cathode to a higher temperature. On the left figure, only one fast wave appeared on the current waveform, that corresponded to the temperature limited case. When the cathode was heated up, gradually two space-charge waves with the same amplitude and opposite polarity appeared, which was the case presented in section 2.3. Eventually, only one slow wave appeared on the current waveform, as shown in the right figure.

Fig. 7. Current waveforms with perturbation measured from the first current monitor under the same condition except a changing cathode emission.

This property of the space-charge-waves were also demonstrated by the energy analyzer's measurement. Fig. 8 shows three different results from the second retarding field energy analyzer. Each figure was obtained in the same condition as in the corresponding current waveform in Fig. 7. The figure shows the beam current carried by the electrons with an excessive energy above the average beam energy. On the left, an

insufficient cathode emission only produced one fast wave with rather large amount of current above the beam energy. When the cathode was gradually heated up, this current bump gradually reduced, a second peak from the slow wave appeared at some point and gradually increased; then it came to the picture in the middle of the figure where the two space-charge waves had the same amount of beam current. As this process went on, the slow wave peak kept increasing and the fast wave peak continued to decrease. Eventually, we ended up with only one slow wave peak with rather large amplitude.

Fig. 8. Beam current with excessive energy above the average beam energy, carried by the space-charge waves, which were measured from the second retarding field energy analyzer under the same condition except a changing of the cathode emission.

The experimental observation has been confirmed by the theoretical analysis presented in the next section.

2.5. Theoretical analysis of the space-charge waves

This analysis differs from the one often seen in the literature in the following:

- a) The space-charge waves are solved in the time domain for a local perturbation instead of in the frequency domain for a sinusoidal wave.
- b) The specific solutions under the given initial and boundary conditions are obtained instead of the eigenmode solutions from the dispersion equations.
- c) All possible initial conditions of velocity, density, and current perturbations are considered instead of the simplest cases such as a velocity perturbation only, or a density perturbation only.

Starting with the one-dimensional fluid equation and employing the double Laplace transform, one can get the solution of the perturbed beam velocity, density and current in the complex domain with all the possible initial and boundary conditions. Supposing there is no perturbation anywhere along the space coordinate z when $t < 0$, and introducing at $z=0$ (the location of the gun) a velocity perturbation of the form $\alpha v_0 G(\tau)$ where v_0 is the beam velocity, α is a small quantity specifying the perturbation strength and $G(\tau)$ is the unit gate function, the perturbed space-charge waves then have the forms:

$$v_1(z, t) = -\frac{v_0}{2} \left[\alpha - (\beta - \alpha) \frac{c_s}{v_0} \right] \{ U[z - (v_0 - c_s)t] - U[z - (v_0 - c_s)(t - \tau)] \} - \frac{v_0}{2} \left[\alpha + (\beta - \alpha) \frac{c_s}{v_0} \right] \{ U[z - (v_0 + c_s)t] - U[z - (v_0 + c_s)(t - \tau)] \},$$

$$\lambda_1(z, t) = +\frac{\lambda_0}{2} \left[\alpha \frac{v_0}{c_s} - (\beta - \alpha) \right] \{ U[z - (v_0 - c_s)t] - U[z - (v_0 - c_s)(t - \tau)] \} - \frac{\lambda_0}{2} \left[\alpha \frac{v_0}{c_s} + (\beta - \alpha) \right] \{ U[z - (v_0 + c_s)t] - U[z - (v_0 + c_s)(t - \tau)] \},$$

$$i_1(z, t) = +\frac{i_0}{2} \left[\alpha \frac{v_0}{c_s} - \beta + (\beta - \alpha) \frac{c_s}{v_0} \right] \{ U[z - (v_0 - c_s)t] - U[z - (v_0 - c_s)(t - \tau)] \} - \frac{i_0}{2} \left[\alpha \frac{v_0}{c_s} + \beta + (\beta - \alpha) \frac{c_s}{v_0} \right] \{ U[z - (v_0 + c_s)t] - U[z - (v_0 + c_s)(t - \tau)] \}.$$

Here c_s is the "sound velocity" of the space-charge waves, the subscripts 0 and 1 represent the unperturbed and perturbed quantities, respectively, $U(z, t)$ is the two-dimensional Heavyside unit step function, β is an arbitrary number defined by $i_1(0, t) = \beta i_0 G(\tau)$ to specify how much initial beam current perturbation is produced.

The equations above specify in general two space-charge waves for the perturbed beam velocity, density and energy, which have the same waveform as the perturbation. The amplitude and polarity of each wave component depend largely on the relative value of α and β which is actually determined by the cathode emission in the experiment. With different combination of α and β values, the equations yield either one fast wave, or one slow wave, or two space-charge waves with the same amplitude, or anything else in between. The experimental observations can be interpreted very well by these analytical

results. The quantitative comparison between the experiment and the theory is still underway.

2.6. Reflection of the perturbation on the beam edges

We have tried by placing the perturbation very close to the beam edges to determine what happens when the space-charge waves hit the beam edges. Due to longitudinal expansion, the beam edges in the experiment were not sharp, but had a rise and fall time of several nanoseconds which increased with distance along the channel (see Fig. 4). This caused the difficulty to observe the reflection or transmission of the space-charge waves on the beam edges. There is no definite conclusion to draw from the experiment so far. Further effort is needed to resolve this problem. We hope to have a satisfactory report on this subject by the end of this funding period as we have scheduled.

3. Resistive-wall instability experiment

3.1. Theoretical studies

The longitudinal instability has been studied theoretically for space-charge dominated beams in transport channels with complex impedances. Departing from previous studies in this area, we have taken all the relevant parameters including the space-charge force, the complex wall-impedances, and the beam energy spread into account. The growth rates of the instability for monoenergetic beams are discussed in different parameter ranges. The stable regions for hot beams are analyzed with examples.

Our paper [5] entitled "Longitudinal Instability of Space-Charge Dominated Beams in Transport Channels with Complex Wall Impedances" summarizes this study and has been submitted for publication to Physics of Fluids B.

3.2. Status of resistive-wall instability experiment

Preparation of the resistive-wall instability experiment is in progress. We have developed the uniform long solenoid and diagnostic tools such as fast wall-current monitors for this experiment. Improvement of the Farady cup to achieve fast response is underway. A new resistive-wall tube has been produced for us by the Chinese Vacuum Institute in Beijing, though with some nonuniformity problem. A Ph.D physics student, Hyyong Suk, has just joined our group and will carry out the experimental research as a

dissertation. This experiment also requires the short pulse electron beam injector which is now attached to the periodic channel for study of longitudinal compression and propagation of space-charge waves. After the new injector is disassembled from the compression experiment, we can start to assemble the system and to run the experiment. The goal for the first step of the experiment is to measure the growth rate of the slow wave and verify the theory which we have been working on in the past. We plan to start the resistive-wall instability experiment by the summer as we promised in our proposal.

4. Related research not sponsored by this contract

We also have other research projects which are closely related to Heavy Ion Fusion program, but funded by the High Energy Physics Office of the Department of Energy. Since last year, we have conducted longitudinal compression experiment for both parabolic and rectangular beams. Two papers attached in the Appendix report the findings of our experiment. Continuous efforts on this subject are still going on.

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which are related to this research project**

1. J. G. Wang, M. Reiser, W. M. Guo, and D. X. Wang, "Theoretical Study of the Longitudinal Instability and Proposed Experiment", *Particle Accelerators*, vol. 37-38, pp. 181-189 (1992).
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- *6. J. G. Wang, D. X. Wang, and M. Reiser, "Longitudinal Expansion of Space-Charge Dominated Drifting Beam Bunches with a Parabolic Line Charge Density Distribution", Accepted for publication in *Applied Physics Letters*.
- *7. J. G. Wang and M. Reiser, "Longitudinal Instability of Space-Charge Dominated Beams in Transport Channels with Complex Wall Impedances", Submitted for publication to *Physics Fluids B*.
- *8. D. X. Wang, J. G. Wang, D. Kehne, and M. Reiser, "Experimental Investigation of Longitudinal Beam-Envelope Changes of a Drifting Space-Charge Dominated Parabolic Beam", Submitted for publication to *Applied Physics Letters*.

9. J. G. Wang, D. X. Wang, D. Kehne, and M. Reiser, "Propagation of Local Perturbation in Space-Charge Dominated Electron Beams", submitted to the 1993 Particle Accelerator Conference, Washington, D. C., May 17-20, 1993.

* Included in the Appendix.

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